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CO₂ and O₂ MMV framework to quantify potential leaks from geo-sequestration: Technologies for detection for risk abatement

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Outline: MMV Framework for early detection and risk abatement

- Potential CO₂ Leak Scenario
 - Scale, Leak Rate, Footprint, Constraints
 - Fluxes and foot-print: Implications for leaks
- CO₂ Measurement Technologies (scales)
 - Chamber (m), Eddy Flux (10m-km), Remote (10kms-100kms)
- Mammoth Mountain: Natural Analogue
 - Technology applications and integration of results
- Separating Leak from natural background: Strategies
 - Time dependence (diurnal, seasonal)
 - Chemical fingerprinting of CO₂ leak (O₂/CO₂)
 - Tracers: ¹⁴CO₂, perfluorocarbons, ¹³CO₂
- Atmospheric modeling: Leaks to Concentrations
 - Background (vegetation, urban), orography, meteorology
- Mexico City: Urban Analogue

Leak Mechanisms and Paths: Reservoir to Atmosphere

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4. Free Troposphere

$$\text{CO}_2 \text{ (380-500ppm)} = C[\text{Stability}_{\text{Wint/Sum}}, \text{BL-height}_{\text{Day/Night}}, \text{Anthr, Bio, Topo, CO}_2^{\text{source}} (T, P)] \times F_{\text{CO}_2}$$

3. Boundary Layer

CO₂ in situ/column
Eddy Flux
Chamber Flux

$$F_{\text{CO}_2} = F_{\text{LV}}^{\text{CO}_2} + F_{\text{bio}}^{\text{CO}_2} + F_{\text{anth}}^{\text{CO}_2}$$

Biosphere (Photo, resp) +
Anthrosphere (Auto, Industry)

$F_{\text{r}}^{\text{CO}_2}$ = Soil Respiration

$F_{\text{LV}}^{\text{CO}_2}$
2. Vadose Zone
Advection and Diffusion

(Porosity, Tortuosity, Water, Thickness)

CO₂ Profiles

Fractures

$F_{\text{F}}^{\text{CO}_2}$

Geochemistry (Bore, Caprock)

3-D Seismic

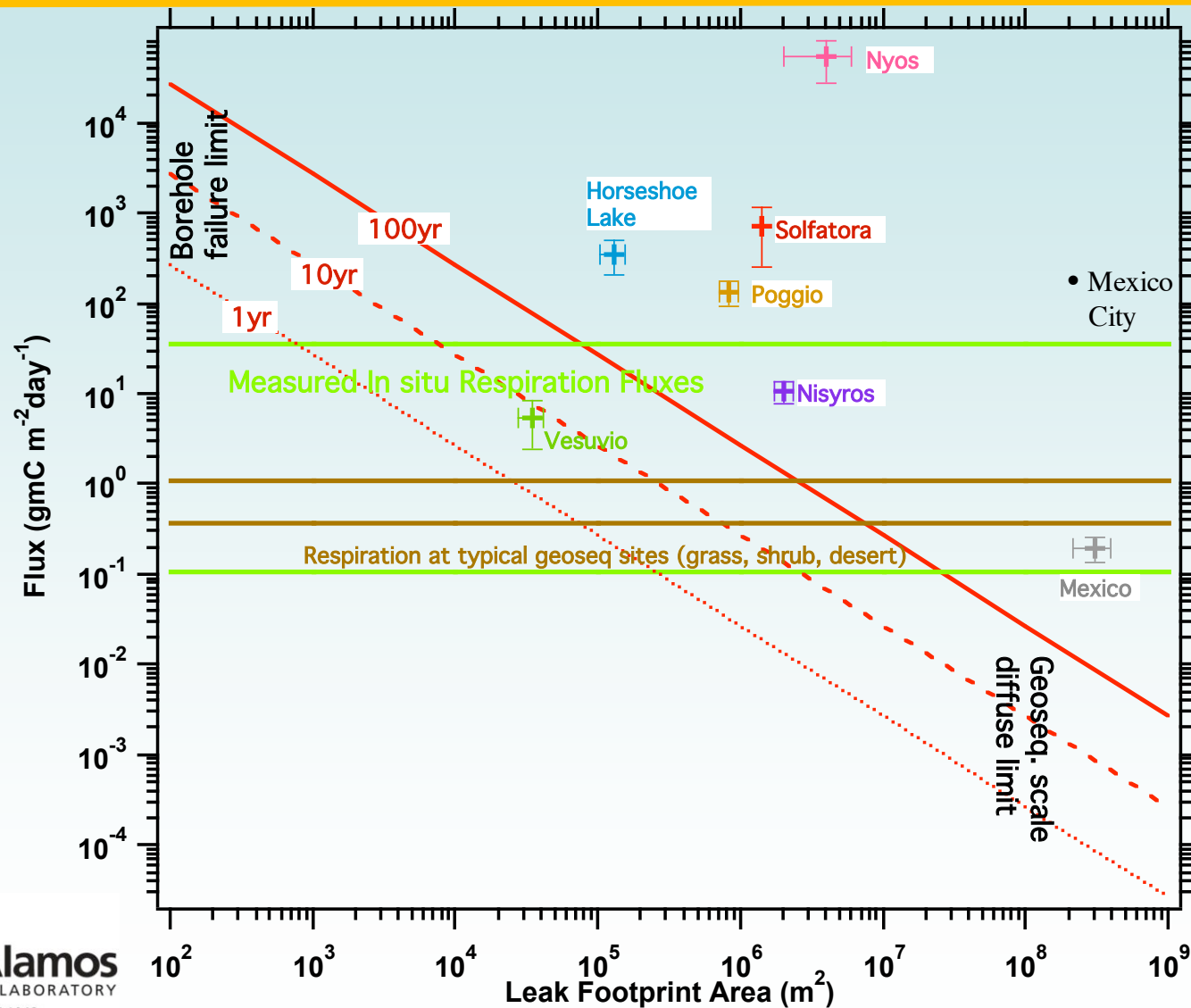
1. CO₂ Reservoir
(supercritical)

Potential Storage and Leak Scenario for Detection Metric

- 1 Megawatt zero emission coal fired power plant
- 3.6 Mtons CO₂/year captured and sequestered
- ~ 4 times Sleipner and Weyburn sequestration rates
- Time horizons of 1, 10 and 100 years
- Reservoir size 3.6, 36 and 360 Megatons of CO₂
- Leak rate 0.01%/year of reservoir size
- Spatial scale of sequestration site ~ 10 km
- Leak flux ~ (Leak rate)/(Leak path area)
- Leak path area variable: bore type~10² m² to diffuse~10⁸ m²

Leak Flux vs footprint compared to natural/city analogues

1 MW plant CO₂ storage reservoir after 1, 10, 100 yrs at 0.01%/year leak rate, 10km scale



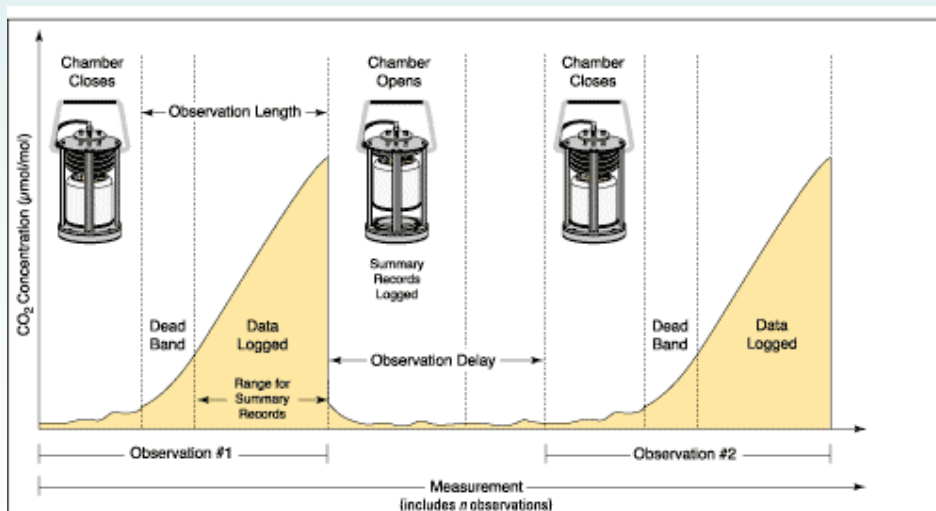
Easy to Detect

Hard to Detect

Accumulation Chamber Measurements of CO₂ Flux

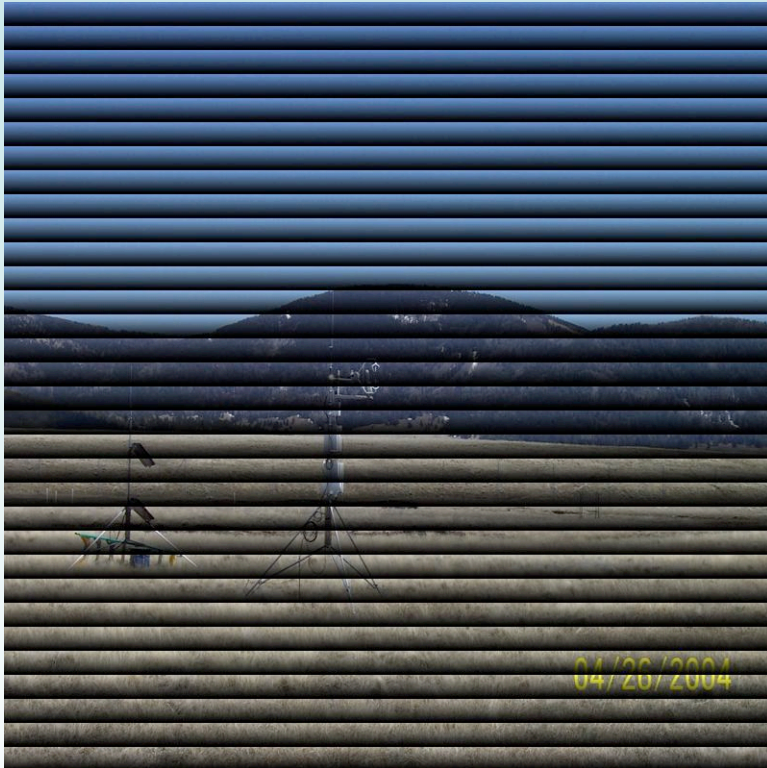


LICOR-8100



Scale ~ 0.1 to 1m²
 Commercial
 Cost \$20K/unit
 Labor Intensive

Valles Caldera Grasslands: LANL Eddy Flux Site



Flux = $\langle v(t)CO_2(t) \rangle$
3-D sonic anemometer
Open path NDIR CO_2 at 10 Hz

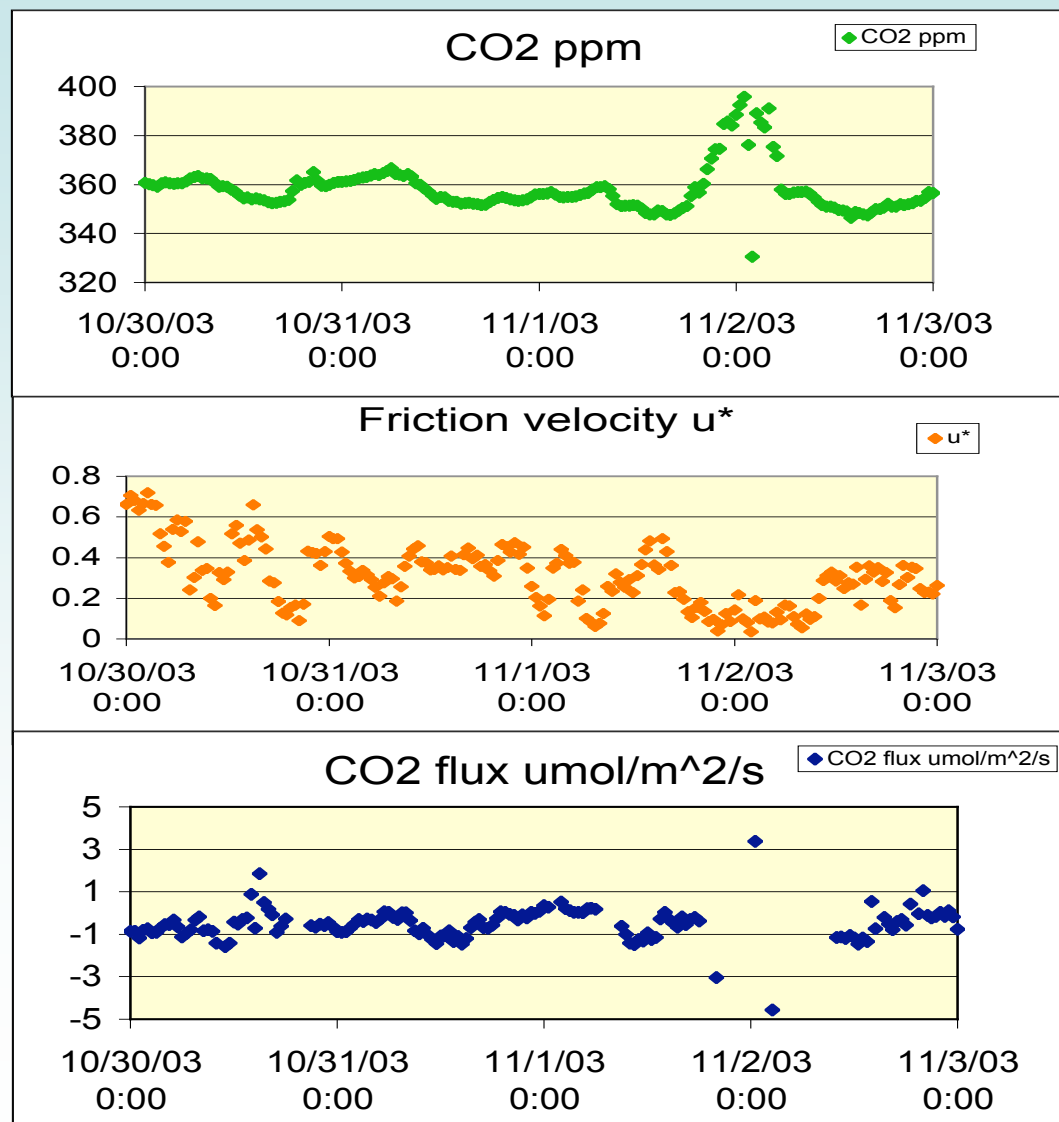
Goal: Determine how grazing influences carbon sequestration.

Methodology: The covariance of simultaneous, collocated, high frequency measurements of vertical velocity and CO_2 concentrations can provide CO_2 surface fluxes under turbulent conditions.

Fetch is \sim Horizontal velocity x tower height upwind ($3m \times 4m/s \sim 12m$), scales with tower height ($400m \sim 1.6km$).

Cost \$50K/unit, automated but extensive data analysis is required.

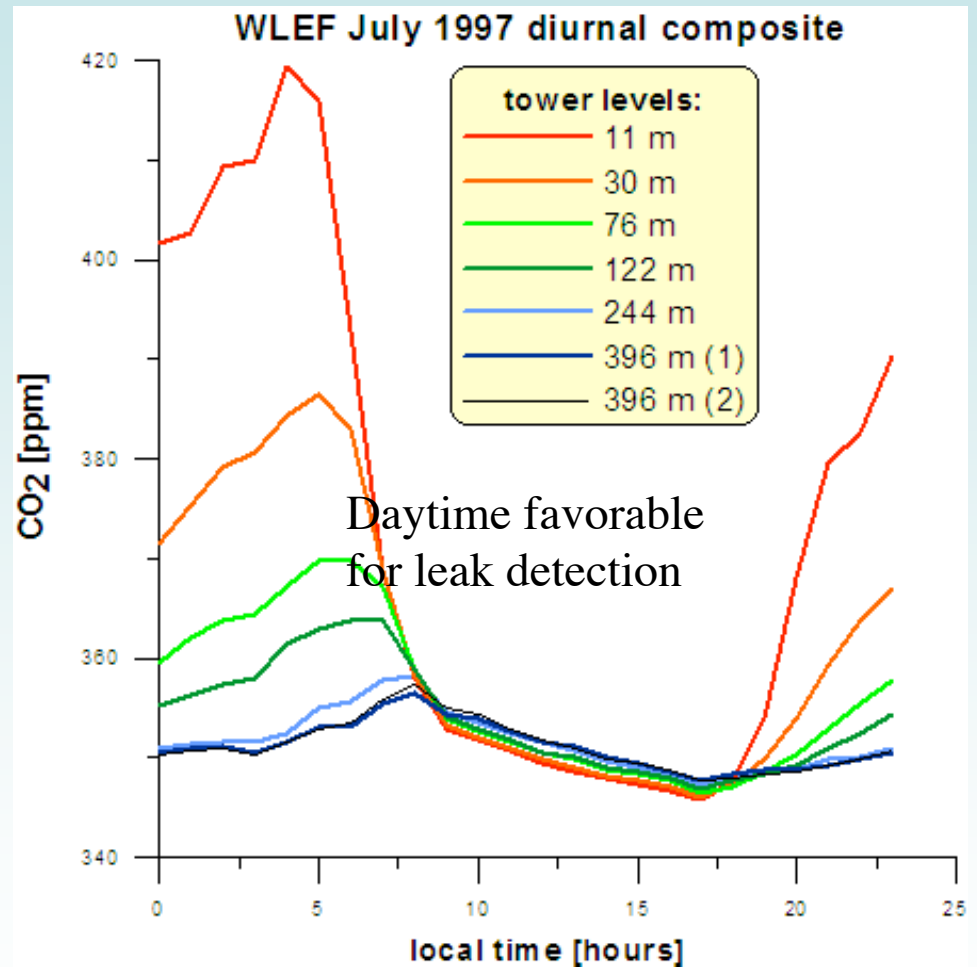
Typical CO₂ Eddy Flux Data



Diurnal Cycle of CO₂ at Wisconsin LEF (400m)



Fetch ~ 400m, 1.6 km of scale as geosequestration sites



Ground-based solar absorption (FTS) of column CO_2/O_2



Figure 4. A Bruker FTS is housed inside a 20-foot shipping container. The facility is fully automated. Currently located at Caltech, it will be shipped to Park Falls, WI in early May.

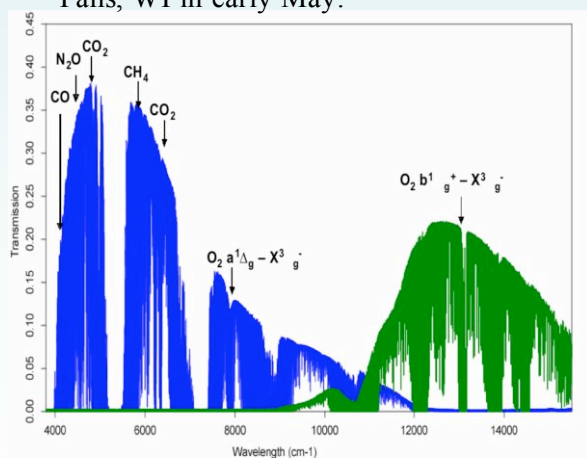


Figure 5. Near IR spectra of the sun obtained at Caltech. Absorption by numerous trace gases are obvious. Two room-temperature detectors are recorded simultaneously: blue – InGaAs; Green – Si.

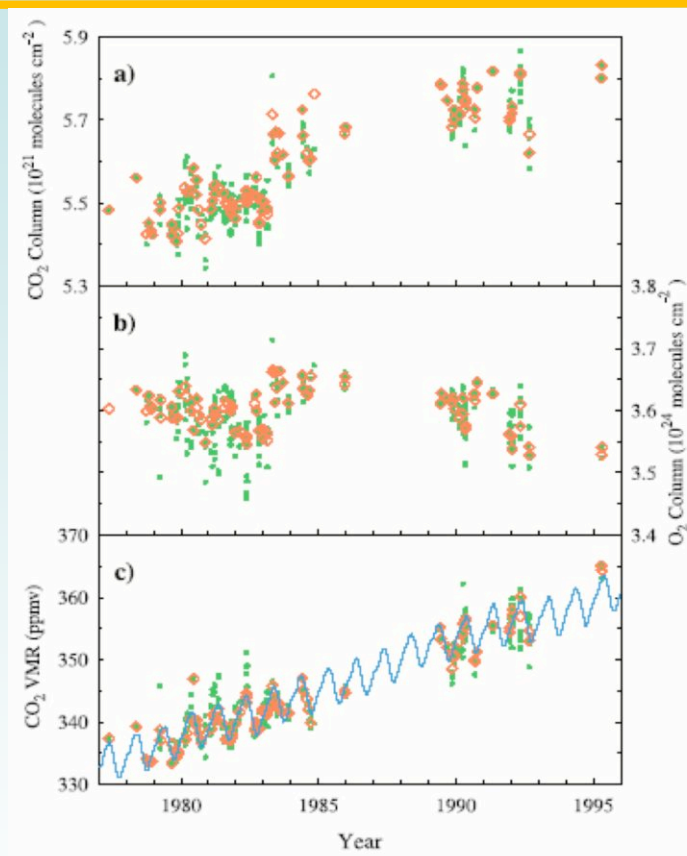
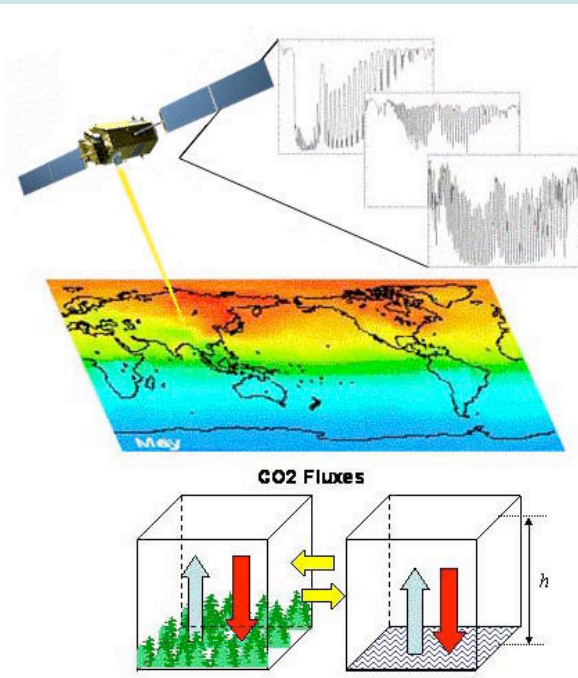


Figure 6. Measurements of the column O_2 (top), CO_2 (middle), and the ratio CO_2/O_2 from Spectra obtained at Kitt Peak.

Can detect ~ppm change in column!
Fetch ~ few km

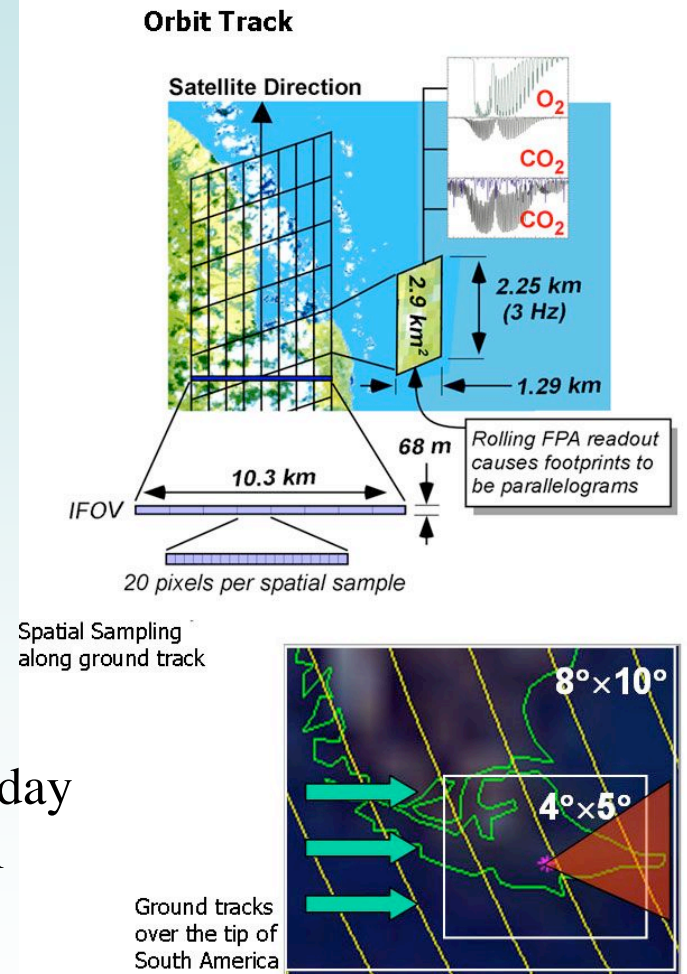
Paul Wennberg, Caltech. Yang et al GRL 103

Observing Carbon Observatory Satellite: Launch in 2008



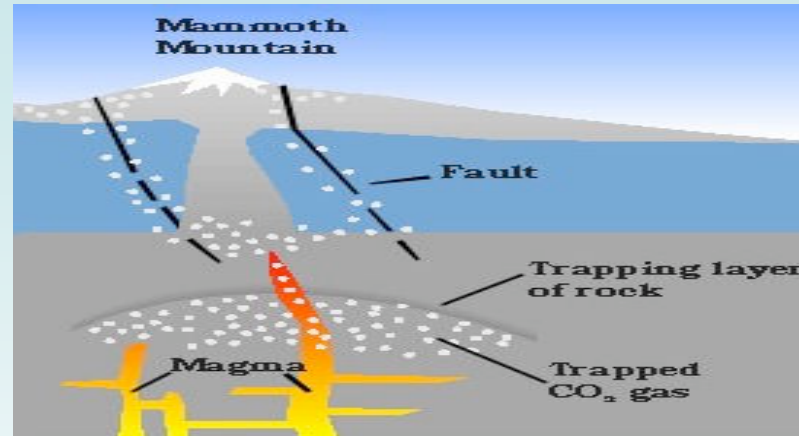
FT-NIR of sunlight reflected by earth

Global Coverage, Sunsynchronous orbit
 1.18 pm observation at each location every day
 Fetch of raw spectral data about 3km x 3km
 Product 1x1 deg CO₂ column to 1ppm



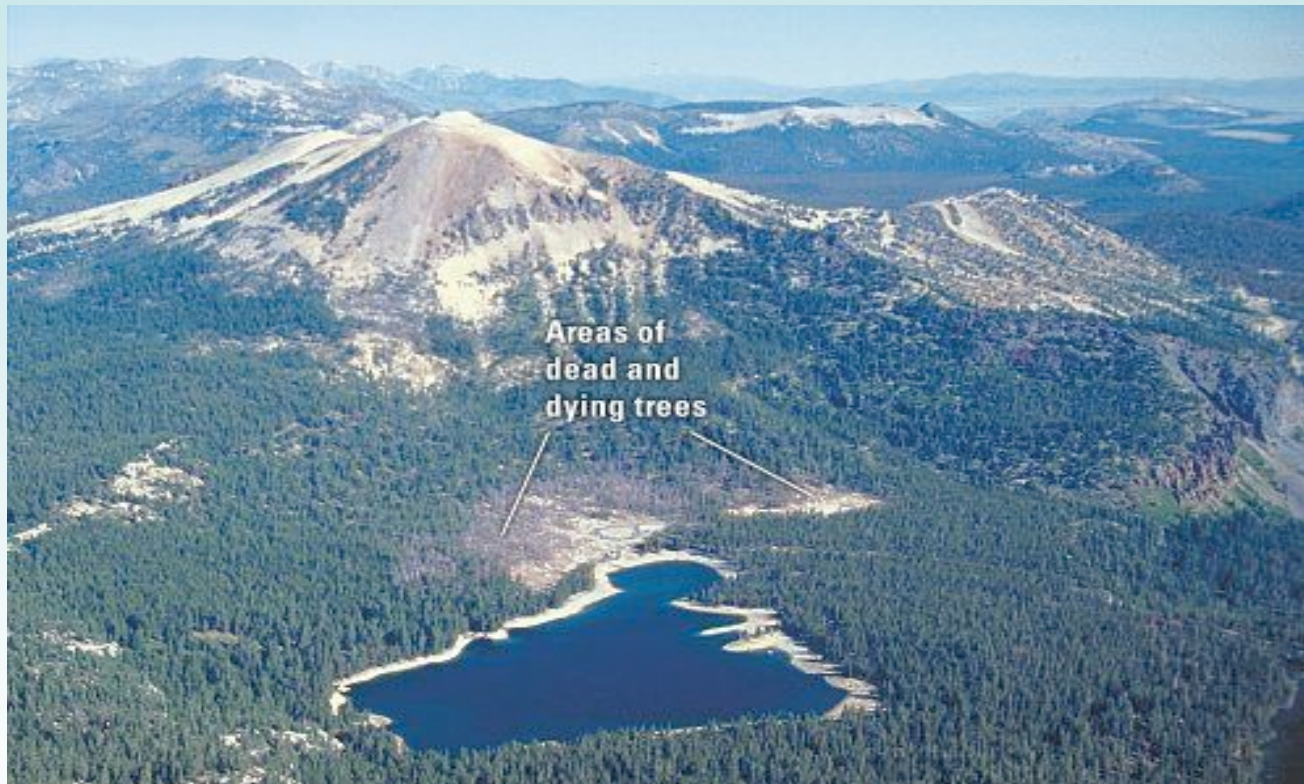
Mammoth Mountain: Natural laboratory for understanding and monitoring CO₂ leakage from geo-sequestration

- 200 kyr old Dormant Volcano in Sierra Nevada active 700 yr ago



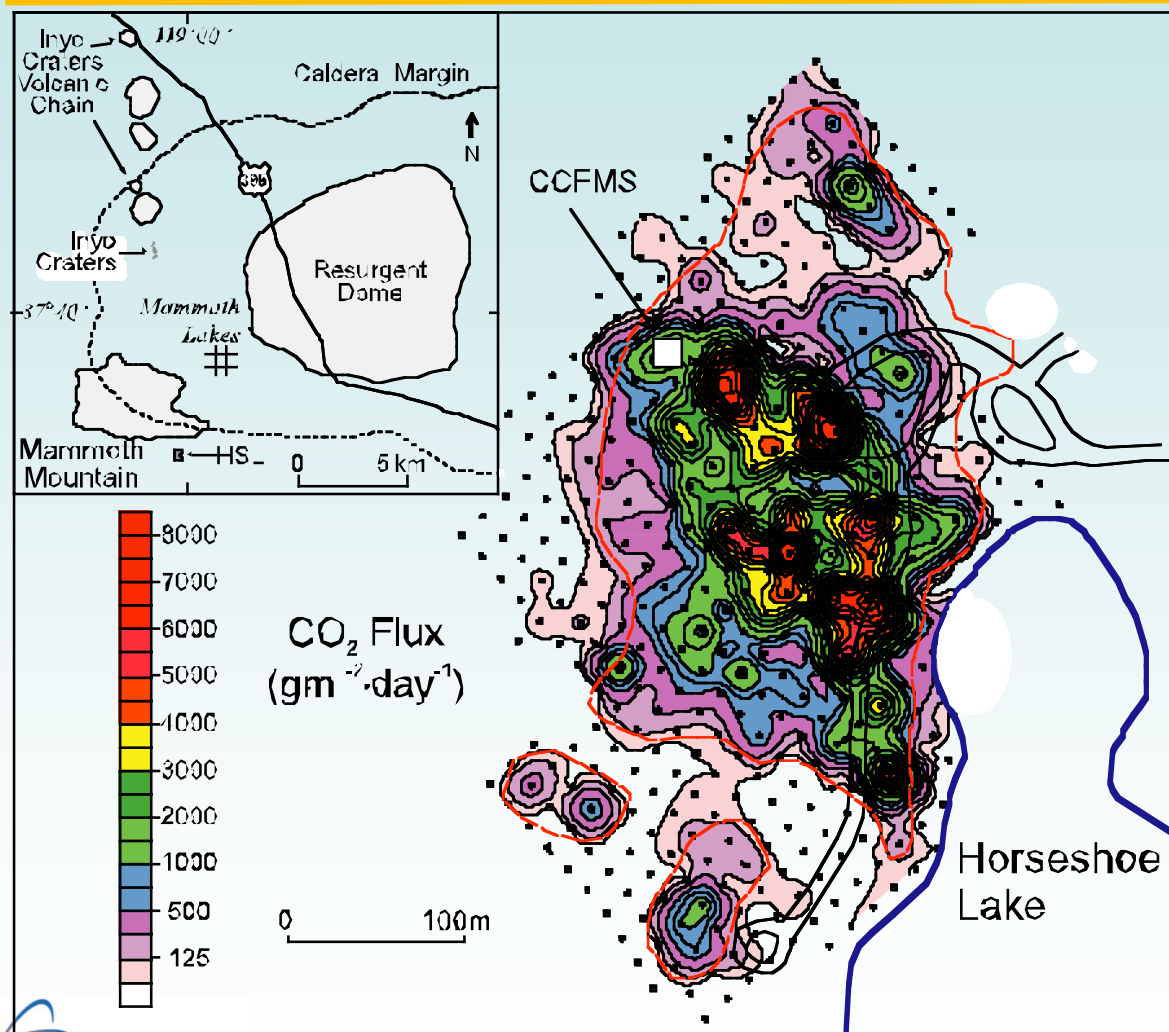
- 1990, series of earthquake swarms (6 months) initiate CO₂ degassing
 - Magmatic CO₂ reservoir at 2-4 km depth
 - High permeability soils; Faults/fractures enhance permeability
 - Tree kills (Horseshoe lake) observed over large areas
 - Toxic CO₂ levels (15-90%) common in soil and snow pack
 - CO₂ in air above depressions can accumulate to lethal levels (skier deaths, '98 & '06)
 - Extensively studied by chamber, eddy-flux, aircraft campaigns

Tree kills at Mammoth Mountain, CA



Ecological impacts of CO₂ leaks are real and should be addressed.
CO₂ induced asphyxia has killed people (3, few weeks ago)

Accumulation Chamber Observations of CO₂ fluxes



Grid of 425 chambers.

Soil biological flux is
 $<15 \text{ g m}^{-2} \text{ d}^{-1}$, used
 $25 \text{ g m}^{-2} \text{ d}^{-1}$ cutoff for
 magmatic CO₂ efflux

Net Flux: 133 tons/day

Footprint: 200m x 500m
 $\sim 100,000 \text{ m}^2$ area

$\langle \text{Flux} \rangle$: $1330 \text{ g m}^{-2} \text{ d}^{-1}$

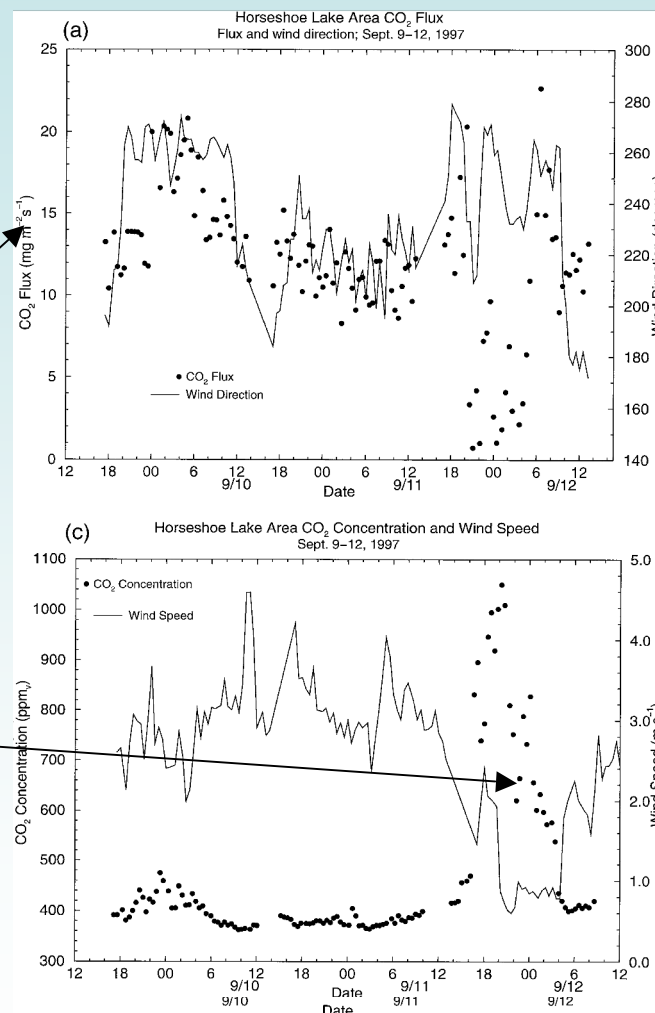
Highest: $8000 \text{ g m}^{-2} \text{ d}^{-1}$

Eddy Flux Observations at HSL (1996-1998)

2 m height

Fluxes 700-1400 g m⁻² d⁻¹
comparable to chamber studies

High wind dissipates CO₂ from
boundary layer by mixing



Chemically Fingerprinting CO₂ Source Plume Using O₂

Respiration & Combustion produce CO₂ and consume O₂ stoichiometrically (~1:1)
e.g. $C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O$

Stored CO₂ should have negligible CO₂
Leaks increase CO₂ without influencing O₂

O₂/CO₂ measured in air at Trinidad traced N. California fires 10/8 to 10/21 1990 plumes, 70 km away.
Can discriminate smoky and flaming fires from slope.

Lueker, Keeling, Dubey
UCSD-LANL, GRL-2001

Wilfire data

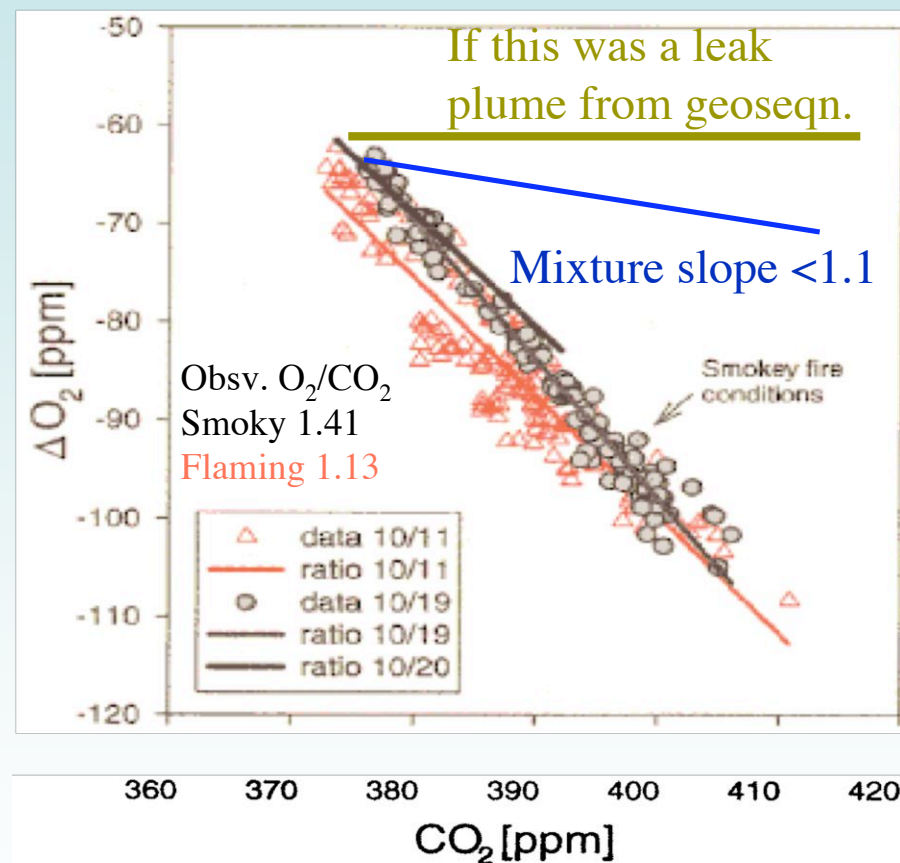
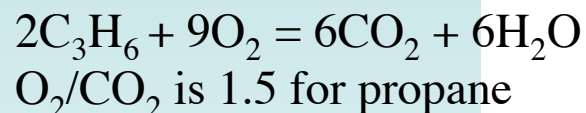
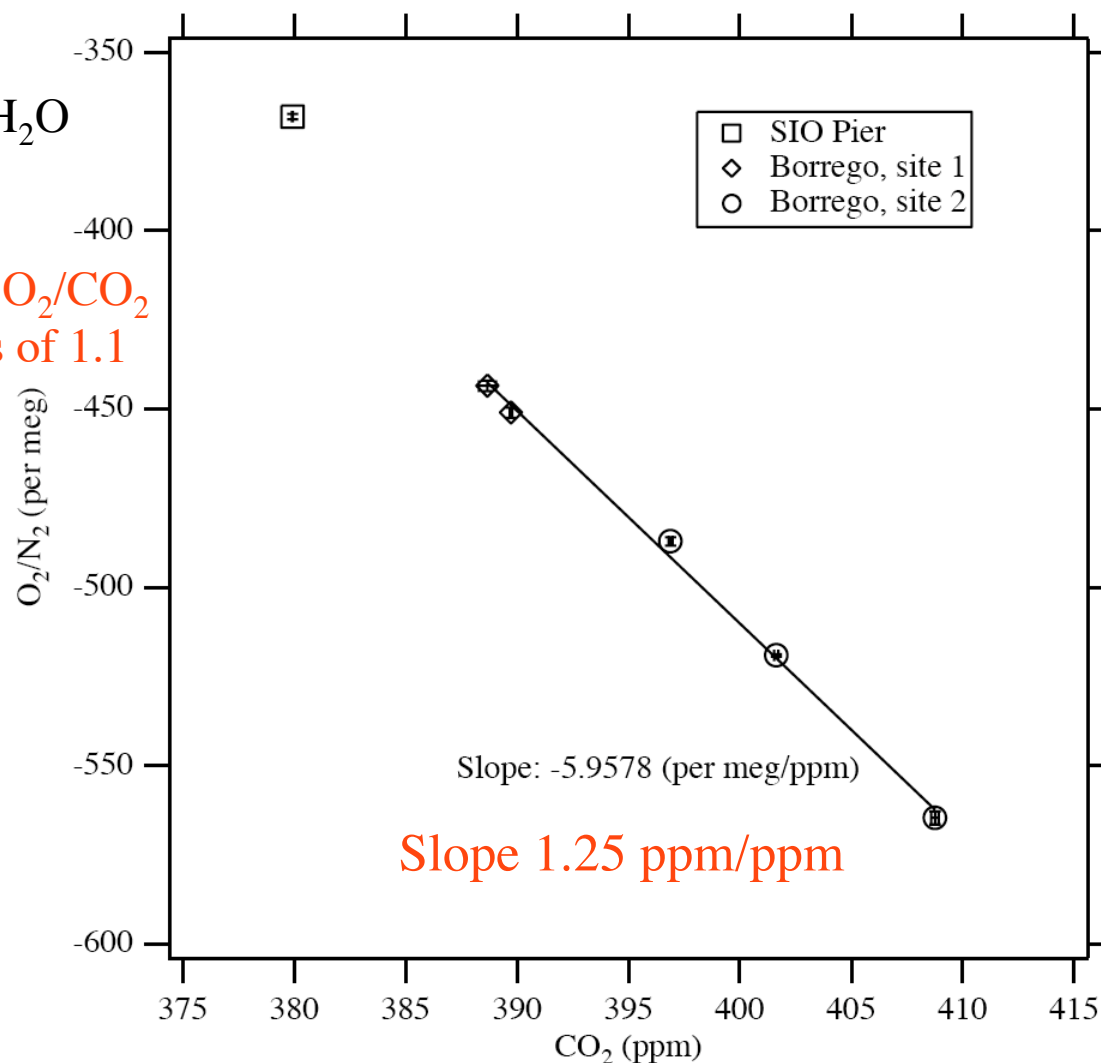


Figure 2. Changes in atmospheric O₂ vs. changes in CO₂ observed on 10/11 and 10/19. O₂ changes expressed in units equivalent to CO₂, i.e. ppm = (per meg / 4.8).

Proof of principle: Fingerprint Propane Leaks Borrego CA

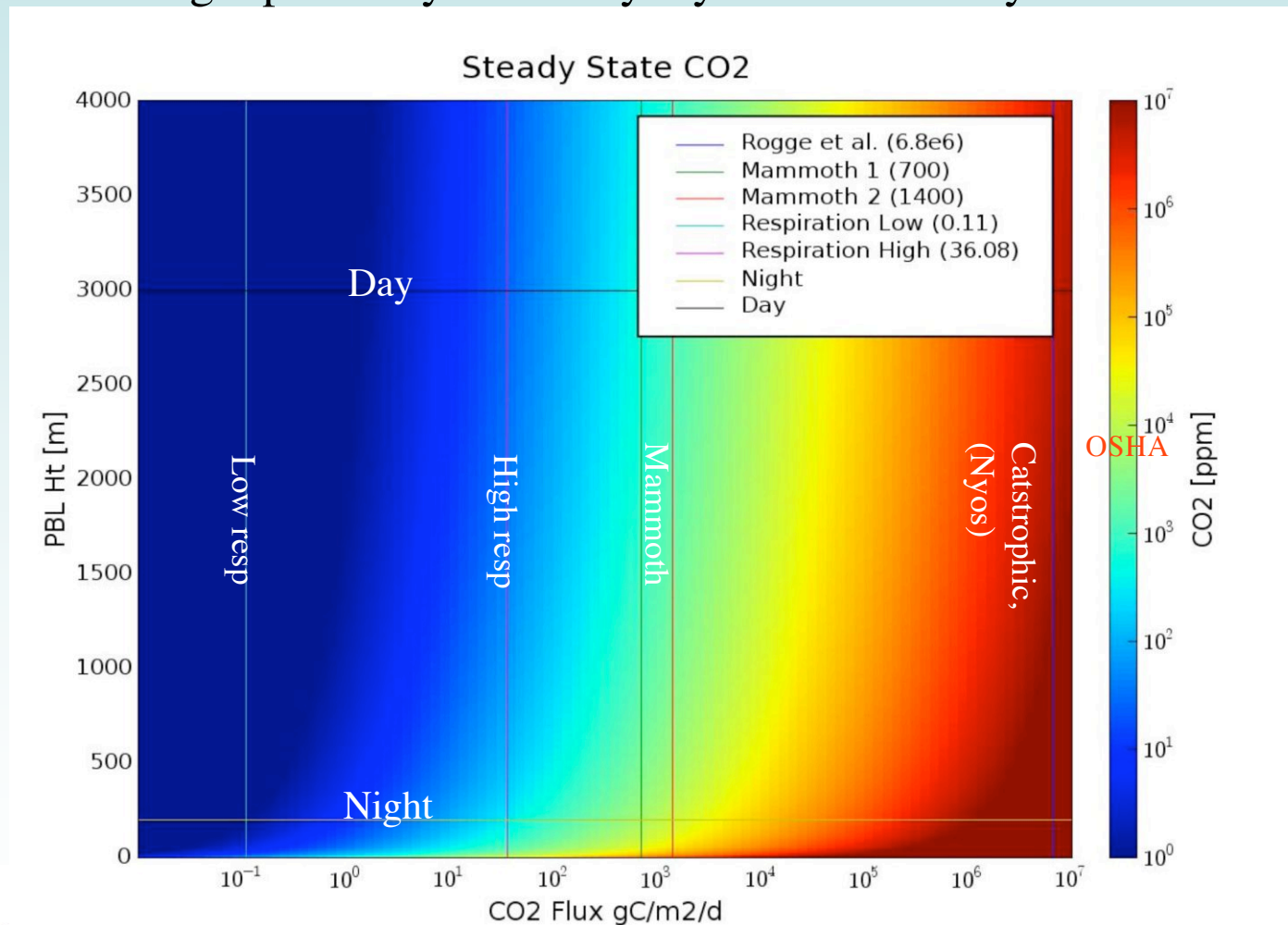


Propane leaks increase to O_2/CO_2 1.25, above typical values of 1.1

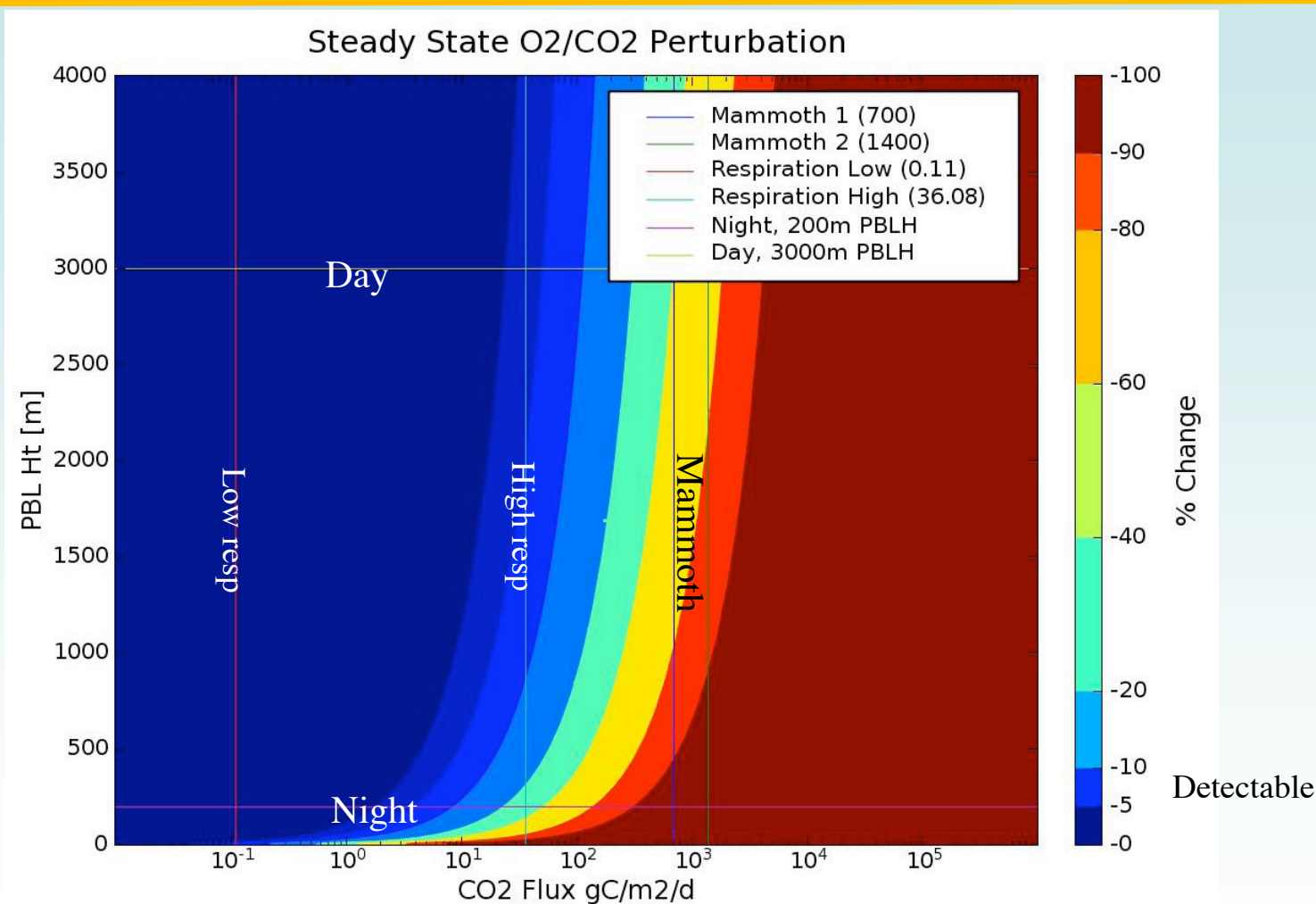


Sensitivity of atmospheric CO₂ to leak flux

Single planetary boundary layer box at steady state



Sensitivity of O₂/CO₂ to Leak: Single Box Model

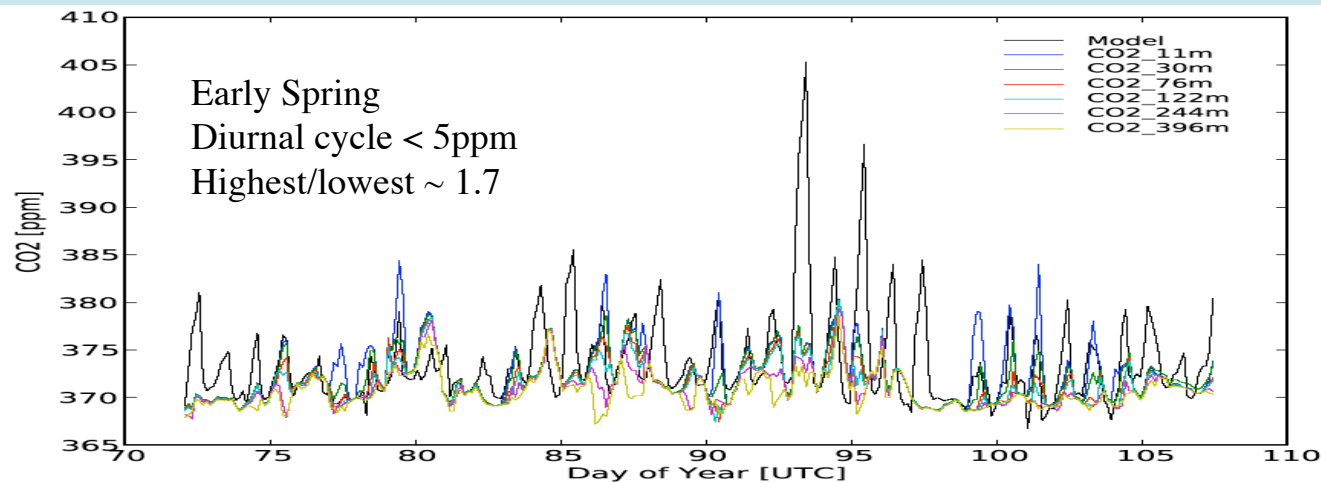


O₂/CO₂ can sense leaks > 0.5 gC m⁻² d⁻¹, CO₂ (time, Mexico) yields similar limit

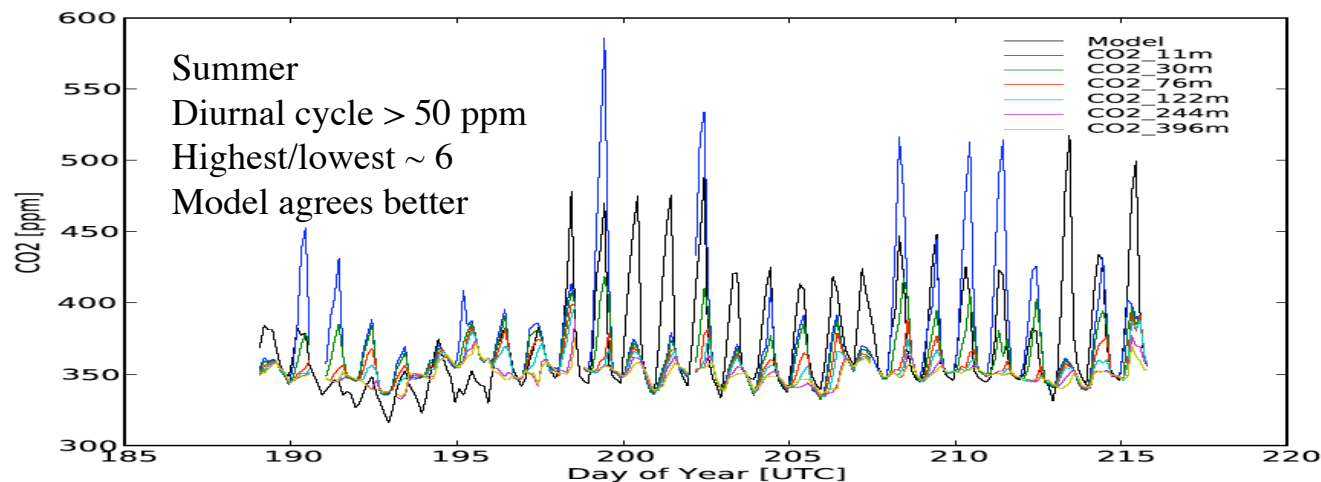
Atmospheric CO₂ Modeling: Fluxes to Concentrations

- Mixed layer Model: Boundary layer (BL) and Free troposphere (FT)
- BL shallow at night and deepens during day by solar heating
- BL depth from NASA, GMAO, GEOS-1 data-model assimilation
- Constrained by surface winds and water fields
- BL shallow at night and grows during daytime
- Applicable to diffuse leaks in flat terrain with large footprint
- Our simulations are compared with WLEF tower data
- Assessment of leak detection at geosequestration sites

CO₂ Simulations vs Observations at WLEF tower



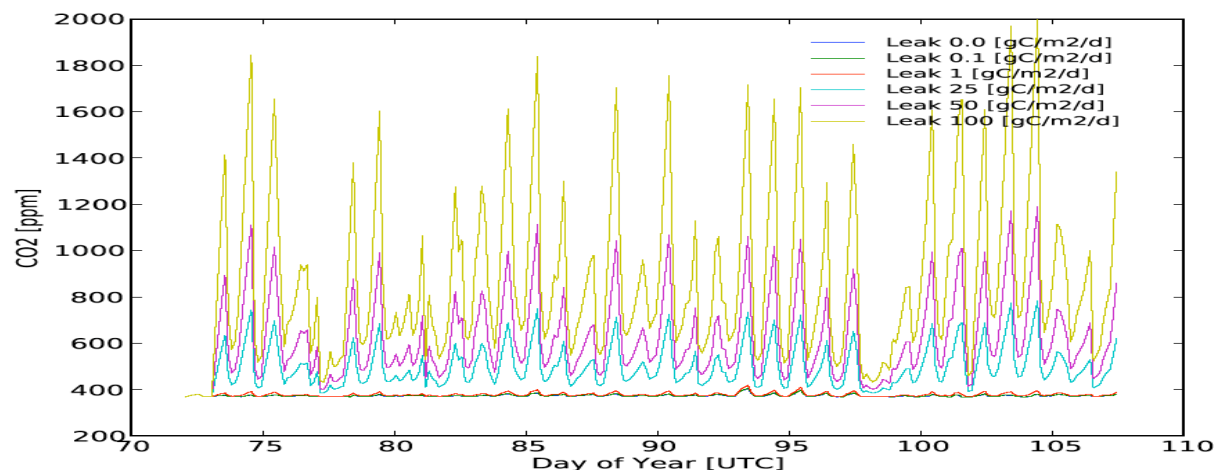
Dormant
Biosphere
Lower fluxes
and variability



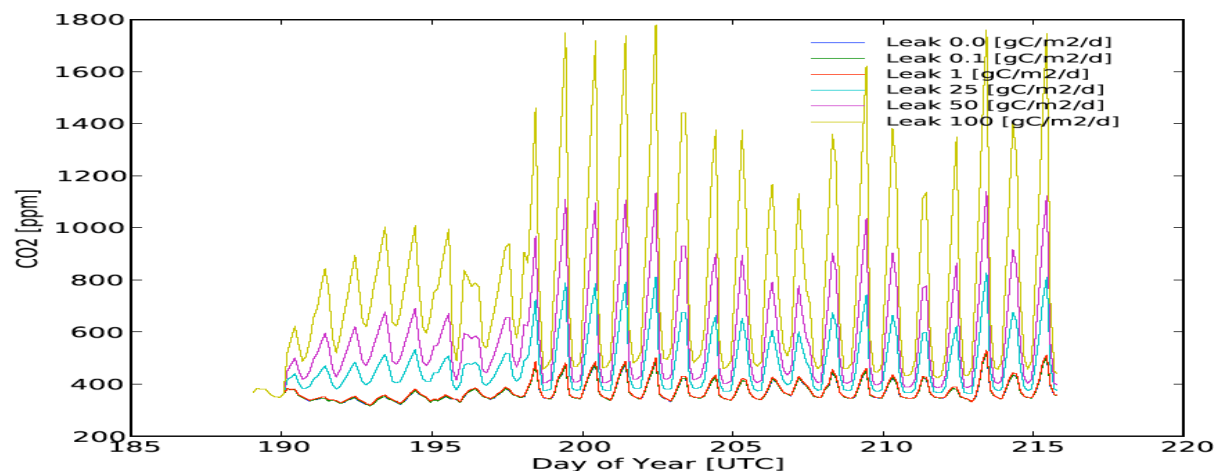
Active
Biosphere
Higher
fluxes and
variability

Seasonal signal can be exploited for leak detection

Simulated leak detection sensitivities at WLEF

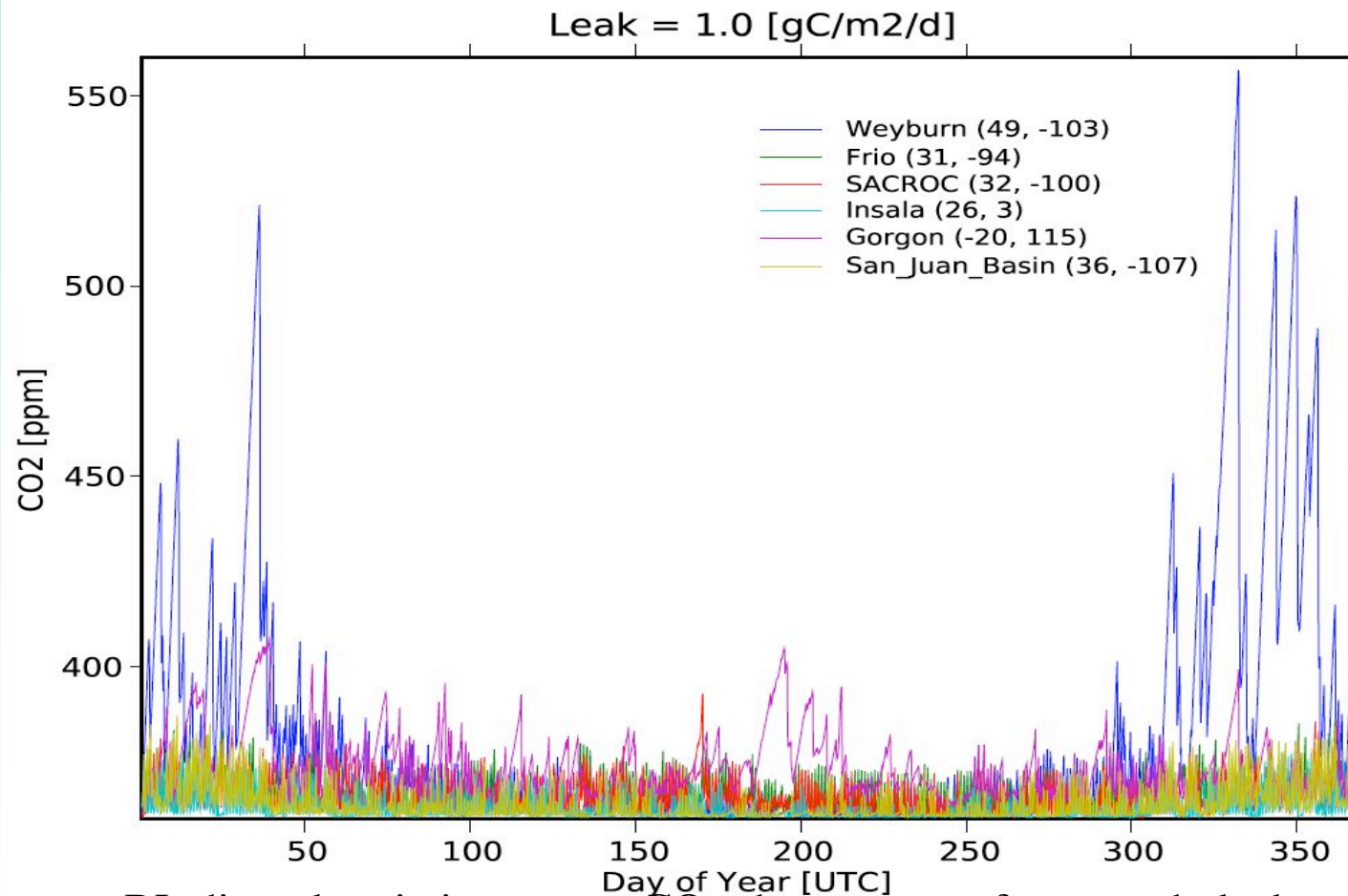


Spring



Summer

Leak detection sensitivity for geoseqn. sites



BL diurnal variations cause CO₂ changes even for a steady leak

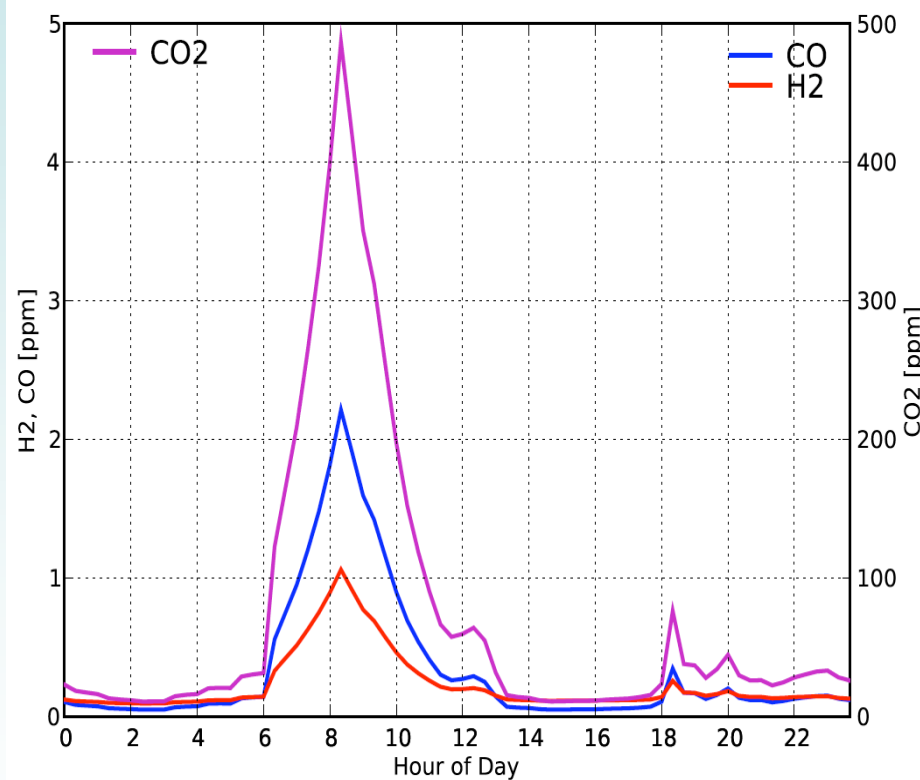
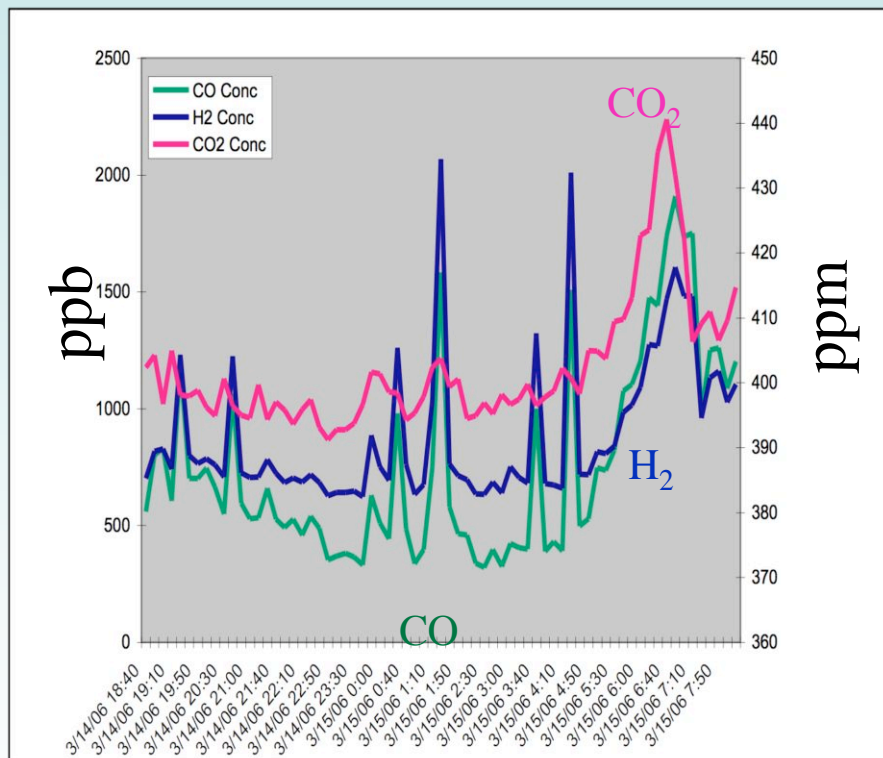
Largest CO₂ increases in winter, especially at Weyburn site

Increases of > 10 ppm above 350 ppm baes are clear at all sites

Urban Analogue: Mexico Mega City CO₂ sources

Observations: MILAGRO 3/06

WRF-CHM Model (3 km res)



CO₂ Emissions ~ 380,000 tons/yr, Area ~ (30km x 10km), Flux ~ 0.2 gC m⁻² d⁻¹

Time dependence of auto emission allows clear resolution of this leak

Conclusions

- Realistic leak scenarios constructed
 - Leak fluxes estimated as a function of leak path footprint areas
 - Compared with natural and urban analogues to quantify risks
- Technologies for leak detection surveyed (LANL expertise!)
 - Commercially available, affordable, and mature
 - Leaks from meter to kilometer scale can be monitored
 - Flux, surface & column concentration measurements can detect leaks
- Mammoth mountain studies: Mature detection technologies
 - Chamber surveys, eddy-flux, aircraft measurements “consistent”
 - Fluxes are high $\sim 1\text{-}10 \text{ kg m}^{-2} \text{ day}^{-1}$, Footprint 100,000-500,000 m^2
- Early detection of leaks within natural background possible
 - Exploit temporal differences (diurnal, seasonal, ned baseline)
 - Chemical fingerprinting of leaks (e.g. O_2/CO_2 , tracers)
- Atmospheric model to determine CO_2 increase from fluxes
 - Early detection and risk abatement is easier at current geoseqn. sites